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COBRA II CORRELATION STUDY & FIELD PERFORMANCE SUMMARY

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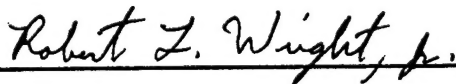
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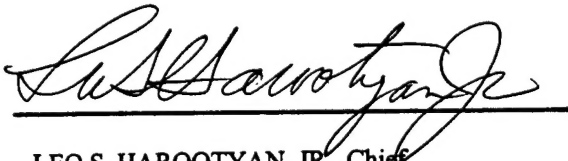
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13. ABSTRACT (Maximum 200 words) <p>A correlation study of the complete oil breakdown rate analyzer, version II (COBRA II) was undertaken to determine the approximate repeatability and reproducibility of data from these oil analysis instruments. Simple root mean square (RMS) equations were used to calculate these parameters. The COBRA II monitors the level of thermal degradation in synthetic, ester-based turbine engine oils. The 95% confidence levels for repeatability and reproducibility were less than 5% and 12% RMS, respectively. The performance of the COBRA II was found to be acceptable and very similar to the repeatability and reproducibility of data from typical Joint Oil Analysis Program (JOAP) atomic emission spectrometers.</p> <p>Additionally, a summary of the field performance to date of the COBRA II is included. The COBRA II has helped to save at least 13 US Air Force turbine engines from oil system (bearing) failure, amounting to savings of about \$39M and a 17,000% return on investment. COBRA II appears to be a very good analytical tool for use in turbine engine maintenance programs where significant oil thermal degradation problems may exist.</p>				
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PREFACE

This technical report was prepared by the Lubrication Branch (WL/POSL), Fuels and Lubrication Division, Aero Propulsion and Power Directorate, Wright Laboratory, which is a part of Air Force Materiel Command (AFMC), at Wright-Patterson Air Force Base, Ohio. The work herein was accomplished under Project 3048, Task 304806, Work Unit 30480618 during the period July - October 1997, with Dr. Robert L. Wright, Jr. as the project engineer.

Special recognition is given to the technical and administrative aid of Ms. Sarah Riegel, science teacher at Ankeney Junior High School, Beavercreek, Ohio and participant in the 1997 "Wright Connection" Program. Special thanks are extended to NAECO Associates, Arlington VA for free use of a COBRA II instrument during the testing period. Also, thanks to Pratt & Whitney, West Palm Beach FL, and Spectro, Inc., Littleton MA for data and reference information.

Finally, and most importantly, special acknowledgment is earned by all Air Combat Command (ACC) and AFMC aircraft maintenance personnel who participated in this study at Seymour Johnson, Elmendorf, Nellis, Eglin, Langley, and Luke Air Force Bases. These are people whose vigilance and tireless efforts help to keep our Air Force the most ready and capable in the world.

1. INTRODUCTION AND BACKGROUND

The complete oil breakdown rate analyzer¹⁻³, version II (COBRA II) is being fielded at most US Air Force and some Air National Guard bases which have F-15 or F-16 aircraft powered by the Pratt&Whitney F100 turbine engine. The COBRA II is a new model of an instrument which monitors the thermal degradation level of synthetic ester-based turbine engine lubricants, such as MIL-L-7808 and MIL-L-23699 (now MIL-PRF-7808 & 23699) oils. The instrument works by measuring the relative electrical conductivity of a thin film of oil. The conductivity of an ester lubricant increases with thermal degradation, and COBRA II takes advantage of this phenomenon by increasing in reading with increase in conductivity of the oil. The instruments cost about \$4,500 each. Fielding of the COBRA IIs for F100 engine oil analysis was necessitated by a number of engine oil thermal breakdowns due to bearing compartment over-temperature events, colloquially known as the F100 "black oil problem". Recently, trending and absolute limits of COBRA II readings have been established for the F100 engine⁴, and a number of these engines have been "saved" by appropriate maintenance actions instituted after COBRA II analysis indicated an impending black oil problem.

Although COBRA II is not recommended for use in monitoring programs for most turbine engines which have very little tendency to significantly thermally degrade the lubricant, it can enhance safety and be quite cost-effective when applied to analysis of oil from engines which have a history of thermal degradation problems. Use of COBRA II and its predecessor, COBRA, have been successful in detecting oil degradation problems and saving millions of dollars in the TF34 and F100 engine programs.

The original COBRA instruments, which were analog electronic devices, were fielded at most A-10 (TF34 engine) bases in the early 1980s due to an oil thermal degradation problem which resulted in engine mainshaft fracture. These COBRAs were highly successful in trending the oil and detecting impending failures in the TF34. The TF34's oil problem was eventually traced to a poorly designed oil sump seal, which allowed hot gas path air into the oil compartment. The seal was redesigned and the oil problem ceased after retrofit. The COBRAs were then taken out of service circa 1985, when their use was no longer cost-effective.

In the early 1990s, the F100 engine began to experience No. 5 bearing compartment over-temperature events, which led to oil thermal degradation, and came to be known as the F100 black oil problem. In 1993 COBRA was upgraded with digital electronics and fielded at several F100 bases for testing of its ability to trend F100 oil and detect impending distress due to black oil. Although the testing was partially successful, with at least six instances of COBRA detecting an impending problem, the F100 program office at Kelly AFB TX felt that maintenance personnel could sufficiently detect black oil just as well as COBRA by using their eyes and nose to determine the dark coloration and burned smell of an abnormal oil sample. They also felt that COBRA had failed to prove

that it could adequately trend the problem. Therefore, COBRA was withdrawn from the field in early 1994.

However, the black oil problem continued. Sight and smell, being highly subjective, were proving to be very uncertain identification methods and many black oil incidents escaped detection. Meanwhile, scientists and engineers from the Air Force and Pratt & Whitney realized that COBRA still had excellent potential to detect this problem, but needed further improvement. This was especially true with respect to the complaint by field personnel in the past that there was too much "drift" in the readings. By this, they meant that sometimes the COBRA reading would tend to creep higher as long as the one kept the "On" button depressed. It was often difficult to make a call on what the actual reading should be. This was a legitimate concern that was relayed to the COBRA manufacturer, NAECO Associates, Inc., Arlington VA. To address the concern, the author worked with the COBRA inventor and lead NAECO engineer in 1995 to diagnose the cause of the drift problem. It was traced to a key resistor in the analysis/readout electrical circuit that sometimes allowed back leakage of current into the readout module. This back leakage caused the liquid crystal display (LCD) readout to increase as one continued to depress the On button. The simple solution to the problem was replacement of the culprit resistor with a similar resistance diode. The diode allows current flow in only one direction, thereby eliminating the potential for back leakage. After the diode was installed, the drift problem was minimized and confidence in the readings has improved.

In 1996, some bases which had experienced a number of black oil incidents purchased COBRAs to supplement their sight/smell detection method. Several engines were saved by corrective maintenance actions taken after COBRA indicated an impending black oil failure. Tragically in 1996, there were two aircraft lost due to the black oil problem, because maintenance personnel were unsure if the oil was dark enough or smelled burned enough to make a black oil call⁵. The Air Force subsequently decided that reliance on subjective human senses was no longer an adequate defense against this problem. Too many black oil events had escaped detection by maintenance personnel, and an objective diagnostic method was sought. COBRA was chosen as the best available technique for detection of this particular problem. It was decided to change the name to COBRA II, to make clear this was a new version of the instrument. The Air Force began purchasing and fielding COBRA IIs on a widespread basis in April 1997. They are now in service at most USAF F100 bases. The Air National Guard also has COBRA II at many of its bases.

The oil problem in the F100 engine has been traced to overheating of the No. 5 (and in rare cases, the No. 4) bearing compartment, which is located in the low pressure turbine (LPT) module. An Air Force/Pratt & Whitney integrated product team (IPT) studied the problem in 1993-94 and recommended a redesign of the No. 5 compartment, which included providing additional heat shielding to the bearing's oil supply and scavenge tubes. Unfortunately, due to funding shortfalls, the IPT recommendations for retrofit were not implemented until 1997. The new components are expected to alleviate

the black oil problem, analogous to the success of the TF34 oil sump seal retrofit of the last decade. Until the retrofit is complete and proven to stop the black oil problem, however, COBRA II will be an important part of the F100 engine condition monitoring program. As of September 1997, approximately 60% of USAF's F100 engines had undergone the No. 5 retrofit.

Pratt & Whitney submitted a component improvement program (CIP) proposal in early 1997 for a field service evaluation (FSE) to track and analyze the data from COBRA II over its first months in operation⁶. This CIP was approved in March 1997, and ran until October. It includes recommendations and lessons learned on the field performance of COBRA II. As a part of this program, six lead bases plus Wright Laboratory (WL) at Wright-Patterson AFB OH were requested to participate in a correlation study of COBRA II performance with respect to repeatability and reproducibility of readings. Since the author has extensive experience with COBRA and COBRA II, he was asked to make up the samples and conduct the data analysis for the correlation study. The following sections of this report detail the study findings and summarize the field performance to date for COBRA II.

2. EXPERIMENTAL

The COBRA II is a relatively simple instrument which measures the ability of a thin film of oil to conduct electricity. When synthetic ester-based lubricants undergo significant thermal stress, acids, alcohols, and other electrical charge carrier species are formed which increase the conductivity of the oil. COBRA II readings increase with increase in conductivity of a fluid, thereby providing a means to monitor the relative level of thermal degradation within an ester lubricant. A picture of the instrument is shown in Figure 1. The COBRA II measures 10 x 5 x 5 inches, about the size of a child's lunch box. It weighs just under 7 pounds.

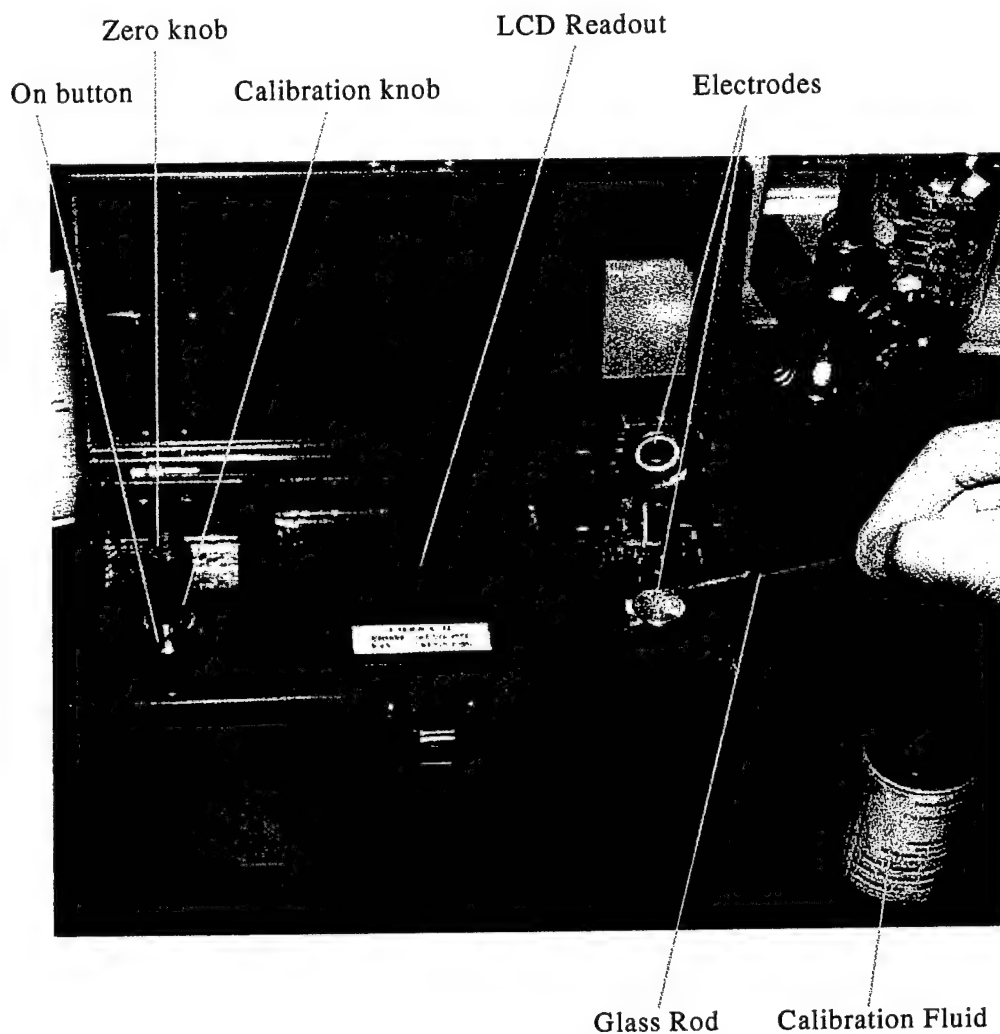


Figure 1. COBRA II Oil Analyzer

In application, a glass rod or pipette is dipped into the sample and one or two drops (~0.025 - 0.05 ml) of oil are placed on the bottom electrode disk. The rod or pipette is then used to "spread" the oil so that the bottom electrode is completely covered, forming a thin oil film. The hinged, top electrode is then brought down to mate with the bottom electrode, creating an oil film "sandwich" between the two electrodes. The "On" button is then depressed and held until a stable reading appears on the LCD, which usually takes about 2 seconds with COBRA II. In the older model COBRA, stabilization sometimes took over 4 seconds or did not occur at all, i.e., the reading would continue to drift higher and higher as long as the On button was held. Field personnel are instructed to take the reading at 4 seconds, if stabilization does not occur before that time. After each analysis, the electrodes are cleaned with a Kimwipe™ and solvent before the next sample is run. It usually takes 15-30 seconds between COBRA II analyses, depending on the operator. The procedure is extremely simple for a laboratory instrument. Most operators can be trained in a few minutes and become proficient shortly thereafter.

COBRA II readings are integer, dimensionless numbers. It has been suggested to the manufacturer that the readings be related to the SI unit for electrical conductance, known as Siemens (S). One Siemens is equal to one Ampere divided by one Volt ($S = A/V$). The suggestion has been taken under consideration.

The instruments are calibrated daily with an ester-based fluid which gives a COBRA II reading of 8. New ester oils usually read 0 to 2 on COBRA II. Used oil samples from normally operating (no black oil problem) F100 engines typically read 1-4. An increase in reading of 3 or more within 10 hours of operation usually signals that an impending black oil problem is developing. A reading of 10 or more has so far always been indicative of impending or actual mechanical distress. These trending and absolute limits are considered preliminary, and will be modified as appropriate during the current CIP. Samples from engines which have had documented compartment over-temperature events have read anywhere from 10 to above 60, depending on the severity of the situation.

Non-destructive inspection (NDI) laboratories at six lead operational bases and the Lubrication Branch of Wright Laboratory (WL/POSL) at Wright-Patterson AFB were asked to participate in this field performance & correlation study. Several of the bases had 2 COBRA II units in operation, and these were included in the study. In all, 9 COBRA II instruments were evaluated, making this a statistically significant database, beyond the 99% confidence level. Each base received 3 samples, which gave COBRA II readings representative of various levels of thermal degradation. The operators were instructed to run the samples 5 times each, in random order.

Since thermally degraded ester lubricants continue to decompose and increase in conductivity, even when stored at room temperature, more stable, simulated samples were devised for the correlation study. These simulated samples were made from a typical ester lubricant basestock compound, trimethylolpropane triheptanoate (TMPH), with an

electrically conductive fluid added. The TMPH molecule gives a zero reading on COBRA II. The conductive fluid is sold under the trade name Conostan™ Stabilizer, produced by Conoco Inc., Houston TX. It is used as a stabilizer in organometallic standards and contains 85-95% alkylamine alkylaryl sulfonate as the active (conductive) ingredient, with the remainder being white mineral and/or solvent neutral oils. The Conostan™ Stabilizer was added to the TMPH ester in 0.22, 0.75, and 1.4% (by weight) amounts in samples 1, 2, and 3, respectively. These were made to simulate the electrical conductivities characteristic of normal, questionable, and abnormal F100 oil samples.

3. DATA ANALYSIS

Data were analyzed for repeatability and reproducibility by use of simple root mean square (RMS) equations. Repeatability is defined as the measure of data spread from a single instrument, i.e., it is the measure of how well one instrument can repeat its own results. Reproducibility is defined as the measure of agreement of data from one instrument with that of other instruments. The RMS equations are modeled after those used in an earlier study of COBRA field performance³, but are shown again here for clarity.

Repeatability of each lab's results is found by first establishing the RMS value of the sample means measured by that lab.

$$L = (\sum L_i^2)^{1/2}$$

where: L = lab RMS sample means value

L_i = lab mean for sample i

Next, a lab RMS deviation value is found from the RMS of that lab's sample standard deviations.

$$S = (\sum S_i^2)^{1/2}$$

where: S = lab RMS deviation value

S_i = lab standard deviation for sample i

The normalized lab repeatability, in percent, is then determined by dividing the lab RMS deviation value by that lab's RMS sample means value and multiplying by 100%.

$$r_L = 100\%(S/L)$$

where: r_L = lab repeatability value (in percent)

To measure reproducibility, the RMS value of the overall sample means is found.

$$R = (\sum R_i^2)^{1/2}$$

where: R = overall RMS reproducibility value

R_i = overall mean for sample i

Each lab's RMS reproducibility, in percent, is then determined by the normalized difference between the lab RMS sample means value and overall RMS reproducibility value, multiplied by 100%.

$$R_L = 100\%(L-R)/R$$

where: R_L = lab reproducibility value (in percent)

To determine the overall mean RMS reproducibility, the overall RMS standard deviation value is calculated.

$$S_o = (\sum S_{oi}^2)^{1/2}$$

where: S_o = overall RMS standard deviation value
 S_{oi} = overall standard deviation for sample i

The overall mean RMS reproducibility is then found by dividing the RMS standard deviation value by the overall RMS reproducibility value, multiplied by 100%.

$$R_o = 100\%(S_o/R)$$

where: R_o = overall mean RMS reproducibility value (in percent)

The lower the repeatability or reproducibility value (absolute value), the better. That is, a value of zero represents perfect repeatability or exact agreement with the overall RMS reproducibility value, R .

4. RESULTS AND DISCUSSION

Reduced data from all test sites are shown in Table 1. All data are included in these results. None were rejected or treated as outliers. Table 2 gives the RMS values found for this data set.

TABLE 1. Reduced COBRA II Data

<u>Location</u>	COBRA II Readings		
	<u>Sample 1</u>	<u>Sample 2</u>	<u>Sample 3</u>
Seymour Johnson	3±0	7±0	13±0
Elmendorf	3.4±0.55	9±0.71	15.6±0.55
Nellis 1	3±0	9±0	16.2±0.55
Nellis 2	2.8±0.45	8.2±0.45	15±0
Wright-Patterson	3±0	9±0	15±0
Eglin	2.6±0.55	8.6±0.55	15.6±0.55
Langley 1	3±0	8±0	13.8±0.45
Langley 2	3±0	8±0	15±0.71
Luke	3±0	9.4±0.55	17.2±0.45
Overall Mean*	2.98±0.34	8.47±0.79	15.2±1.27

* These values are calculated from the entire data set. See summary statistics in Appendix.

TABLE 2. COBRA II RMS Values

Location	S	L	r_L(%)	R_L(%)
Seymour Johnson	0	15.1	0	-14.7
Elmendorf	1.05	18.3	5.74	3.39
Nellis 1	0.55	18.8	2.93	6.21
Nellis 2	0.64	17.3	3.70	-2.26
Wright-Patterson	0	17.8	0	0.56
Eglin	0.95	18.0	5.28	1.69
Langley 1	0.45	16.2	2.78	-8.47
Langley 2	0.71	17.3	4.10	-2.26
Luke	0.71	19.8	3.59	11.9
Average Value*	0.56	17.6	3.12	5.72
Overall Mean**	1.53	17.7		8.64

* These are merely the average values of the data columns. The average reproducibility is found from the absolute values of the lab reproducibilities.

** These are the overall RMS values, S_o, R, and R_o, respectively.

Correlation Sample Results

Figure 2 graphs the sample means, with standard deviation bars, for all base labs. The approximate 95% confidence intervals are also shown for each sample.

Sample 1 has a conductivity level giving COBRA II readings characteristic of oils from normally operating F100 engines. The overall mean value of the 45 readings from all bases was 2.98 ± 0.34 , giving a relative standard deviation (RSD) of 11.4%. The lowest lab average was 2.6 and the highest was 3.4. The lowest single reading was 2 (3 times) and the highest was 4 (2 times). The data range is only 2, giving confidence that no base would ever mistake this "good" oil sample for a questionable or abnormal black oil problem.

Sample 2 is at a conductivity level which is indicative of a questionable F100 oil sample. That is, the level of thermal degradation would probably be to the point where

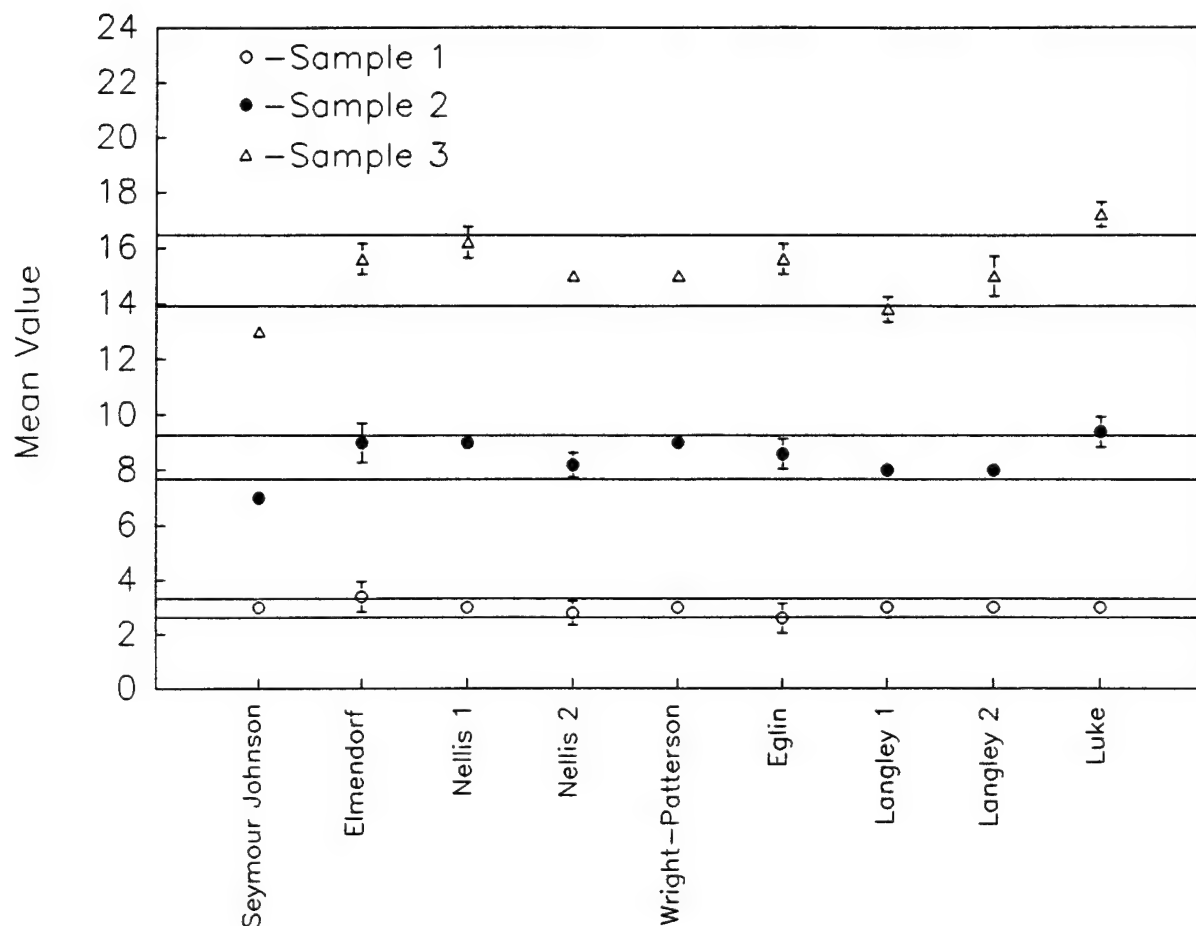


Figure 2. COBRA II Sample Means for all Base Labs

no bearing compartment over-temperature problem had yet surfaced, but an inspection of the No. 5 and/or No. 4 bearing compartments for excessive thermal deposition (coking) is warranted. The overall mean value for this sample was 8.47 ± 0.79 , with RSD of 9.3%. The lowest reading was 7 (5 times) and highest was 10 (3 times). The lowest lab average was 7.0 and the highest was 9.4. There were 17 readings of 8 and 20 readings of 9. Even the base lab at Seymour Johnson, which had all five of the lowest readings, should be able to call for bearing compartment inspection with high confidence that this is a necessary action, based on the deviation in reading from a "normal" oil sample, such as sample 1.

Sample 3 is representative of abnormal oil from an F100 engine in which bearing compartment over-temperature has already begun. The overall mean for sample 3 was 15.2 ± 1.27 , with RSD of 8.3%. The lowest reading was 13 (6 times) and highest was 18 (once). The lowest lab average was 13.0 and the highest was 17.2. There were 5 readings of 14, 17 readings of 15, 10 readings of 16, and 6 readings of 17. All bases

would have easily identified this as a definite problem sample, given the current limit of 10 as a reading value at which maintenance action must be taken.

The summary statistics listed in the Appendix show the average, median, mode, and geometric mean for each sample are very close in value, indicating the data have a strong central tendency. The variance, standard deviation, standard error, range, and interquartile values illustrate the spread or dispersion of data is quite tight. The low skewness and kurtosis values denote that data distribution for each sample is very close to Gaussian normal, although the kurtosis coefficient of sample 1 is a relatively large value of +6.8. This means the data distribution for sample 1 is very steep at the center, which is due to the fact that 40 of the 45 values are readings of 3 (see frequency histogram in Appendix). Skewness and kurtosis values within a range of -2 to +2 for large data sets indicate there is not significant deviation from Gaussian normal distribution. The coefficients of variation, usually referred to as the RSDs, average less than 10%. This normalized measure of data spread reinforces the sense of centralized distribution.

Repeatability and Reproducibility

The average lab repeatability value was found to be 3.12%, while the average lab reproducibility value was 5.72%. These values for COBRA II are 14% and 18% better, respectively, than those found in the 1993-94 field performance study of the older version of COBRA³. The COBRA II overall mean RMS reproducibility value was found to be 8.64%, while for COBRA it was calculated to be 9.71%, but is not listed in the previous report. By this overall measure, COBRA II performed 11% better in reproducibility than COBRA. The repeatability and reproducibility values for each base lab are shown in Figures 3 and 4, respectively, with 95% confidence intervals illustrated.

All lab repeatability values were less than 6%, while all lab reproducibility values were less than 15%, absolute. All but 2 labs had less than 10% normalized difference from the overall RMS reproducibility value. The 95% confidence interval for repeatability is approximately 2-5%, meaning that a single instrument will usually have less than 5% RMS variability when analyzing the same sample. For a worst case analysis, the 99% confidence interval for repeatability shows that RMS variability from a single COBRA II should almost always be less than 7%. The worst lab repeatability value in this study was 5.74%. The 95% confidence interval for reproducibility is about -6 to 6%. This means, in absolute terms, that one can normally expect less than 12% RMS variation in readings from instrument to instrument. The 99% confidence interval for reproducibility is about -15% to 15%. Therefore, one could get an RMS variability from one COBRA II to another of up to 30%, in rare instances. In this study, the total reproducibility value range was -14.7 to 11.9%, or about 27%.

Comparison with JOAP Spectrometer Data

It is also informative to compare the COBRA II data with typical performance data from atomic emission wear metal analysis spectrometers, which are used in routine

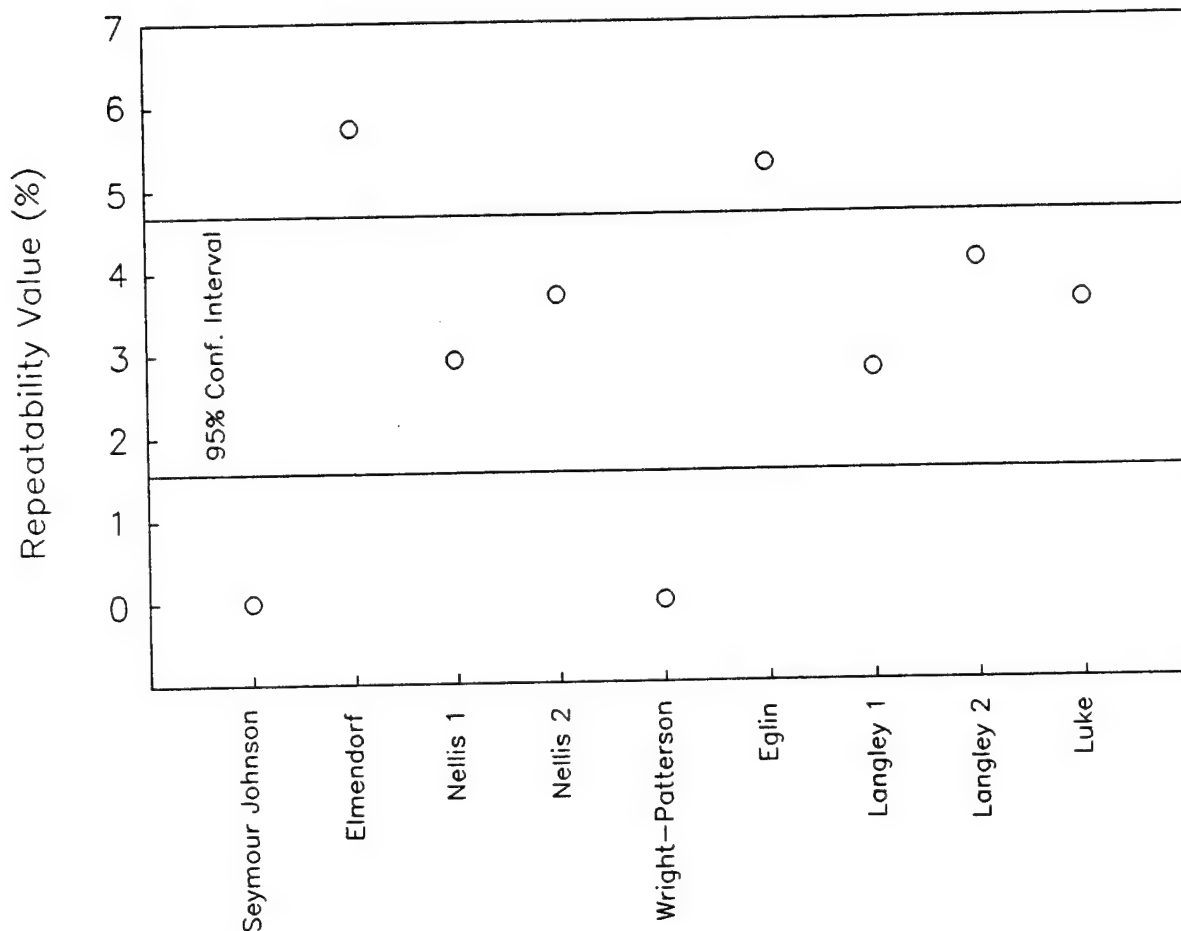


Figure 3. RMS Repeatability Values for all Base Labs

oil analysis at many bases as part of the DOD's Joint Oil Analysis Program (JOAP). It should be noted that the comparison here is only with respect to numerical data. The JOAP spectrometers and COBRA II measure completely different types of oil properties. The COBRA II measures the relative electrical conductivity of oils, while the JOAP spectrometer measures the concentration of wear metal contaminants contained within the oil. The JOAP atomic emission spectrometer has capability to detect the presence of 20 different metals, with varying degrees of sensitivity.

For comparison of COBRA II repeatability with that of the JOAP spectrometer, specification data from a typical JOAP instrument were examined. Table 3 gives the repeatability specifications (allowable standard deviations) for a typical JOAP atomic emission spectrometer⁷.

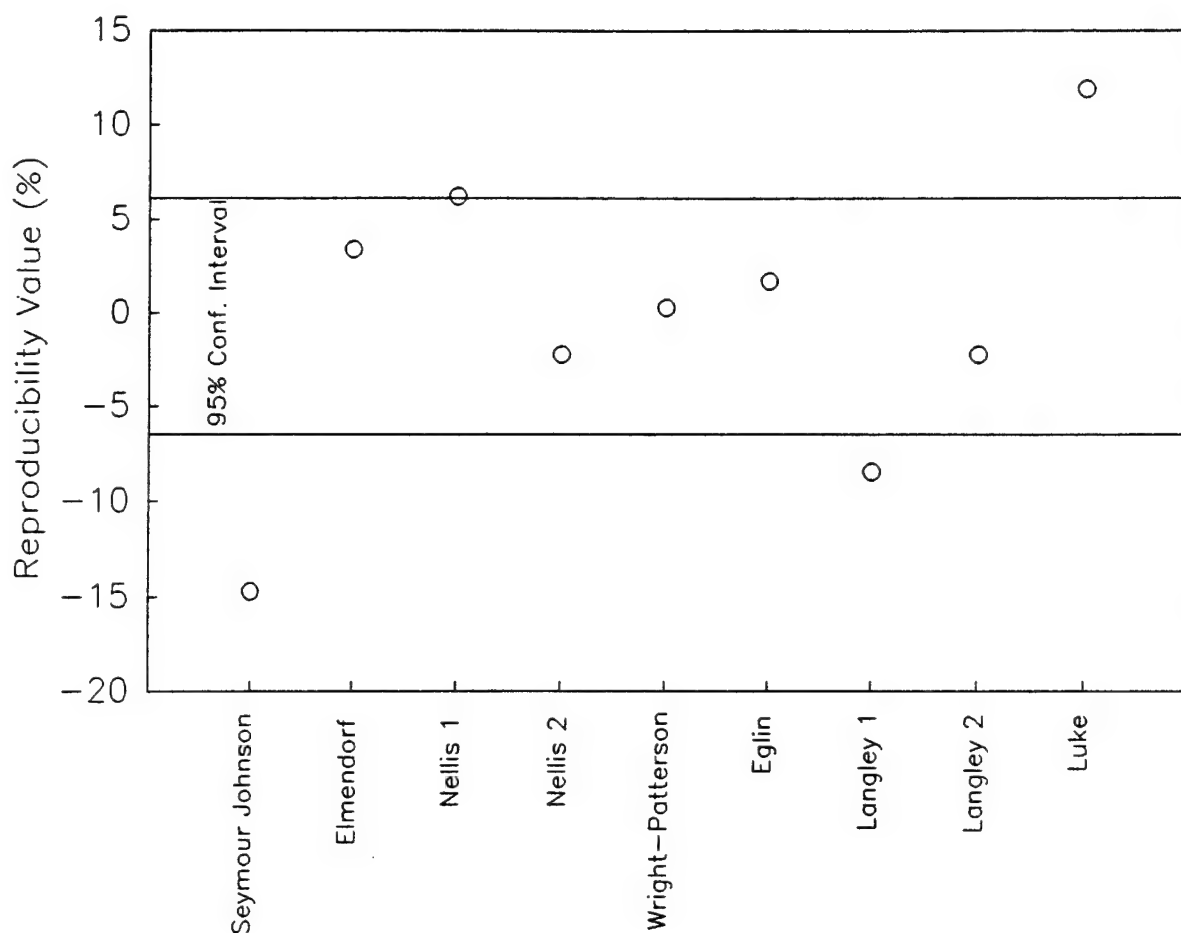


Figure 4. RMS Reproducibility Values for all Base Labs

At a JOAP reading level of 3 parts per million (ppm), the repeatability specification has a range of ± 0.52 to 1.02 ppm or about 17-34% RSD, depending on element. This reading level is comparable to the COBRA II mean of 2.98 for sample 1. The average COBRA II standard deviation for sample 1 was ± 0.17 or about 6%, while the largest was ± 0.55 (18%). The 18% RSD is very close to the tightest JOAP spectrometer specification at this level.

At a JOAP spectrometer reading level of 10 ppm, roughly corresponding to the COBRA II mean of 8.47 for sample 2, the repeatability specifications range from ± 0.71 to 1.30 ppm or about 7-13%. The average standard deviation for COBRA II at this reading level was ± 0.25 (3%). The largest standard deviation was ± 0.71 (8%), approximately equal to the lowest JOAP specification limit at this level.

Linear interpolation of Table 3 between 10 and 20 ppm concentrations, gives a repeatability specification range of approximately ± 0.92 to 1.88 ppm or about 6-13% at a reading of 15 ppm. This reading level corresponds to the mean of 15.2 for sample 3.

TABLE 3. Repeatability Specifications (Allowable Standard Deviations) for a JOAP Atomic Emission Spectrometer⁷

REPEATABILITY SPECIFICATIONS

Conc. PPM	Fe, Al, Be, Cr Cu, Mg, Ni, Si	Ti, B, Ba Cd, Mn	V	Pb	Sn	Ag, Na, Mo	Zn	Conc. PPM
0	0.50	0.50	0.80	0.90	1.00	0.50	0.50	0
1	0.50	0.50	0.80	0.90	1.00	0.51	0.51	1
2	0.51	0.51	0.81	0.91	1.01	0.53	0.55	2
3	0.52	0.53	0.81	0.92	1.02	0.55	0.62	3
4	0.54	0.55	0.82	0.93	1.03	0.59	0.69	4
5	0.56	0.58	0.84	0.95	1.04	0.64	0.78	5
6	0.58	0.62	0.85	0.97	1.06	0.69	0.88	6
10	0.71	0.78	0.94	1.08	1.17	0.94	1.30	10
20	1.12	1.30	1.28	1.50	1.56	1.68	2.45	20
30	1.58	1.87	1.70	2.01	2.06	2.45	3.63	30
50	2.55	3.04	2.62	3.13	3.16	4.03	6.02	50
100	5.03	6.02	5.06	6.07	6.08	8.02	12.00	100
	Al, Be, Cr, Ni, Si, V	Pb, Sn, Ti, B, Ba, Cd, Mn	Fe, Ag, Mo	Cu, Mg	Zn	Na		
300	15.00	18.00	24.00	27.00	36.00	48.00		300
500	25.00	30.00	40.00	45.00	60.00	80.00		500
700	35.00	42.00	56.00	63.00	84.00	112.00		700
900	45.00	54.00	72.00	81.00	108.00	144.00		900
1000	50.00	60.00	80.00	90.00	120.00	160.00		1000

The average standard deviation for sample 3 was ± 0.36 (2%), while the largest was ± 0.71 (5%), which is below the interpolated JOAP spectrometer specification range at this level.

Based on this comparison, the repeatability of the COBRA II instruments tested in this study appears to be quite acceptable with respect to criteria long accepted for JOAP atomic emission spectrometers.

For a comparison of reproducibility of COBRA II with the JOAP spectrometer, one year's data from the JOAP monthly correlation reports⁸ were examined. To simplify the analysis, only data for the element iron (Fe) were evaluated. Iron is the most important wear metal analyzed by the JOAP spectrometer, and is also among the most repeatable and reproducible elements detected by atomic emission. The correlation program values were calculated from the overall true (non-trimmed) means and standard deviations for 4 JOAP samples analyzed by approximately 200 labs each month. The overall monthly RMS reproducibilities for iron over a one year period ranged from 6.0-13%. These values were calculated exactly as for the COBRA II overall mean RMS reproducibility value, R_o , found here to be 8.64%. The yearly average R_o for the JOAP spectrometer was 8.62%, statistically identical to the COBRA II value.

The overall RMS reproducibilities of COBRA II and the JOAP spectrometer appear to be very similar. This should be a statistically valid observation, since the COBRA II database is significant beyond the 99% confidence level and the JOAP data base is so huge as to be considered absolute. COBRA II data appear to be reliable to approximately the same extent as those from the JOAP atomic emission spectrometer.

Field Performance Summary

As of September 1997, nine black oil problems were successfully detected by COBRA II during the field service evaluation CIP⁶. However, there were also three false calls and two precautionary engine removals where no evidence of coking or distress were found. Also, one engine was pulled for scheduled LPT and core time change and found to have internal and external coking of the No. 5 pigtail tube with a COBRA II reading of 4, but no trend data was available (this was first COBRA II reading on the engine). Table 4 details the findings for the 15 engine removals⁶.

Table 4. Engine Removal Findings for CIP Task 320⁶ (COBRA II Field Service Evaluation)

<u>Date</u>	<u>Engine</u>	<u>Base</u>	<u>Reason for Removal</u>	<u>Results of Teardown</u>	<u>Conclusion</u>
4/23/97	680874	Eglin	1 or 2 to 5 increase	Ext./Int. coke on No. 5 Tubes	Save
4/11/97	680644	Elmendorf	7 to 20 one flight increase	No. 5 Oil Supply Tube coked internally	Save
3/3/97	719167	Seymour Johnson	1 to 4 increase	No. 5 Tubes coked internally No. 5 Adapter Jet clogged	Save
2/13/97	681584	Elmendorf	LPT and core time change COBRA = 4	Ext./Int. coke on No. 5 Pigtail Tube. No Cobra trend data.	None
10/24/96	712037	Mt. Home	COBRA = 10	No. 5 Adapter Jet clogged	Save
6 97	719039	Mt. Home	High COBRA	No hardware problems. Oil contaminated by water	False Call
5/21/97	719154	Mt. Home	1 to 5 one flight increase	Evidence of bore fire. No. 5 Adapter Jet plugged	Save
5/9/97	712284	Eglin	3 to 5 jump	No problems found in No. 5 Adapter Jet and Scavenge Tube. Engine RTS	Precautionary Pull
5/8/97	719263	Seymour Johnson	1 to 3 jump	Chunks of coke in the #5 Adapter Jet, Pressure and Transfer Tube	Save
8/21/97	720135	Elmendorf	"4" to "6" readings, dropped to "2", returned to "5"	No findings	False call

<u>Date</u>	<u>Engine</u>	<u>Base</u>	<u>Reason for Removal</u>	<u>Results of Teardown</u>	<u>Conclusion</u>
7/25/97	720076	Elmendorf	Jump 3 to 6 in 3 hrs.	No. 4 Rear Seal Seat oil passages plugged	Save
7/8/97	719306	Lakenheath	COBRA = 10	No. 5 Compartment coked	Save
5/21/97	682284	Eglin	3 to 5 jump	All hardware clean	Precautionary Pull
9/19/97	720137	Elmendorf	"4" avg. reading, dropped to "1", returned to "5"	All hardware clean	False call
N/A	711823	Eglin	1 to 3 increase	Pigtail Tube showed evidence of leakage. Small coke deposits in the No. 5 Adapter Jet	Save

Of the 3 false calls, one was due to an abnormally high concentration of water in the oil, according to the field report from Mountain Home AFB ID. Increased water concentration leads to increased conductivity and, therefore, higher COBRA II readings. The other two false calls occurred when engines were pulled at Elmendorf AFB AK, due to COBRA II readings that dropped by 3 or 4, then rose again to the previous level. The reason for the unusual drop in readings has not been found. There were records of component changes on these engines at the time of the decreased readings, but no report of whether the oil had been changed or not⁹. An oil change or significant addition of new oil could cause such a decrease in reading. If significant new oil addition was not the culprit, then the COBRA II instrument at Elmendorf may not be operating properly. However, personnel there say it appears to be doing fine, with several thousand "normal" readings and 3 saves so far.

At no time has COBRA II yet failed to detect a problem, when one actually existed. There were over 14,000 COBRA II analyses from 523 engines reviewed during the CIP. Over 99.4% of the readings were 3 or less. There were three precautionary engine removals when readings jumped by 2 from the previous flight. No coking or hardware problems were found in two of these pulls, where the COBRA II readings jumped from 3 to 5. However, chunks of coke were found in the No. 5 adapter jet in one of the precautionarily pulled engines, when the reading jumped from 1 to 3. The CIP team has come up with the following lessons learned and recommendations⁶:

LESSONS LEARNED:

1. Water contamination causes false high readings.
2. COBRA II "jump" can be caused by aberrant low reading followed by return to normal trend.
3. Jump of 2 is usually not significant.

RECOMMENDATIONS:

1. Reject engine for COBRA II reading of 10 or above.
2. Reject engine if COBRA II reading increases 3 or more above the average reading for the last 10 operating hours.
3. Drain and flush engine if there is reason to suspect water contamination (look for "cloudy" or "milky" appearance of oil sample; do crackle test or run Karl Fischer titration and drain/flush if above 1,500 ppm H₂O).
4. Investigate if COBRA II reading decreases from previous reading.

Fifty COBRA II instruments have been purchased to date at a total cost of \$225K. Nine engine saves have been documented so far during the CIP. Additionally, COBRA II is responsible for at least 4 other F100 engine saves prior to the CIP. Therefore, savings to the F100 program are at least \$39M, based on an estimated \$3M for each F100 engine. This is a return on investment (ROI) of over 17,000%! COBRA II is having an extremely positive impact on the F100 maintenance program and should remain in the field until such time as the current No. 5 bearing compartment retrofit is completed and proven to alleviate this engine's black oil problem.

5. CONCLUSIONS

COBRA II data are found to be repeatable and reproducible within a 95% confidence interval of less than 5% and 12% RMS, respectively. The newer COBRA II shows approximately 10-15% better performance in these parameters than the older version of COBRA. The repeatability and reproducibility levels for COBRA II are found to be acceptable and very similar to the performance criteria for data from the widely used JOAP atomic emission spectrometer.

The field performance of COBRA II has been very good so far, with at least 13 engine saves. Savings to the F100 engine maintenance program attributable to use of COBRA II are estimated to be at least \$39M, with a return on investment of over 17,000%. The COBRA II is a cost-effective and safety enhancing instrument, when used in turbine engine maintenance programs where significant oil thermal degradation or coking problems exist.

6. REFERENCES

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2. Centers, P. W. and Smith, H. A., "COBRA Analysis of Laboratory Degraded Synthetic Turbine Engine Lubricants", *J. Syn. Lubrication*, 1 (3), Deal, Kent UK, October 1984.
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6. "CIP Task 320 - COBRA", COBRA II Field Service Evaluation, Pratt & Whitney, West Palm Beach FL, March - October 1997.
7. "Spectroil Jr Operation and User Maintenance Manual", Technical Manual, Spectro Incorporated, Littleton MA, January 1991, p. A-2.
8. "JOAP Monthly Correlation Reports", Technical Reports, Joint Oil Analysis Program-Technical Support Center (JOAP-TSC), Naval Air Station, Pensacola FL, February 1990-January 1991.
9. Telephone Communication with Leonard, B., Service Engineer, Pratt & Whitney, West Palm Beach FL, 17 November 1997.

Appendix

COBRA II Summary Statistics and Raw Data

Summary Statistics

09/30/97

03:10:59 PM

Variable:	Sample1	Sample2	Sample3
Sample size	45	45	45
Average	2.97778	8.46667	15.1778
Median	3	9	15
Mode	3	9	15
Geometric mean	2.95757	8.43027	15.1256
Variance	0.113131	0.618182	1.60404
Standard deviation	0.33635	0.786245	1.26651
Standard error	0.0501401	0.117207	0.1888
Minimum	2	7	13
Maximum	4	10	18
Range	2	3	5
Lower quartile	3	8	15
Upper quartile	3	9	16
Interquartile range	0	1	1
Skewness	-0.41732	-0.178775	-0.0690084
Standardized skewness	-1.14288	-0.489595	-0.188987
Kurtosis	6.80986	-0.343161	-0.393639
Standardized kurtosis	9.32478	-0.469893	-0.539013
Coeff. of variation	11.2953	9.28636	8.34448
Sum	134	381	683

~ 95% CONF. INTERVAL: 2.64 - 3.32 7.68 - 9.26 13.9 - 16.5			

Raw Data

FILE: COBRACOR

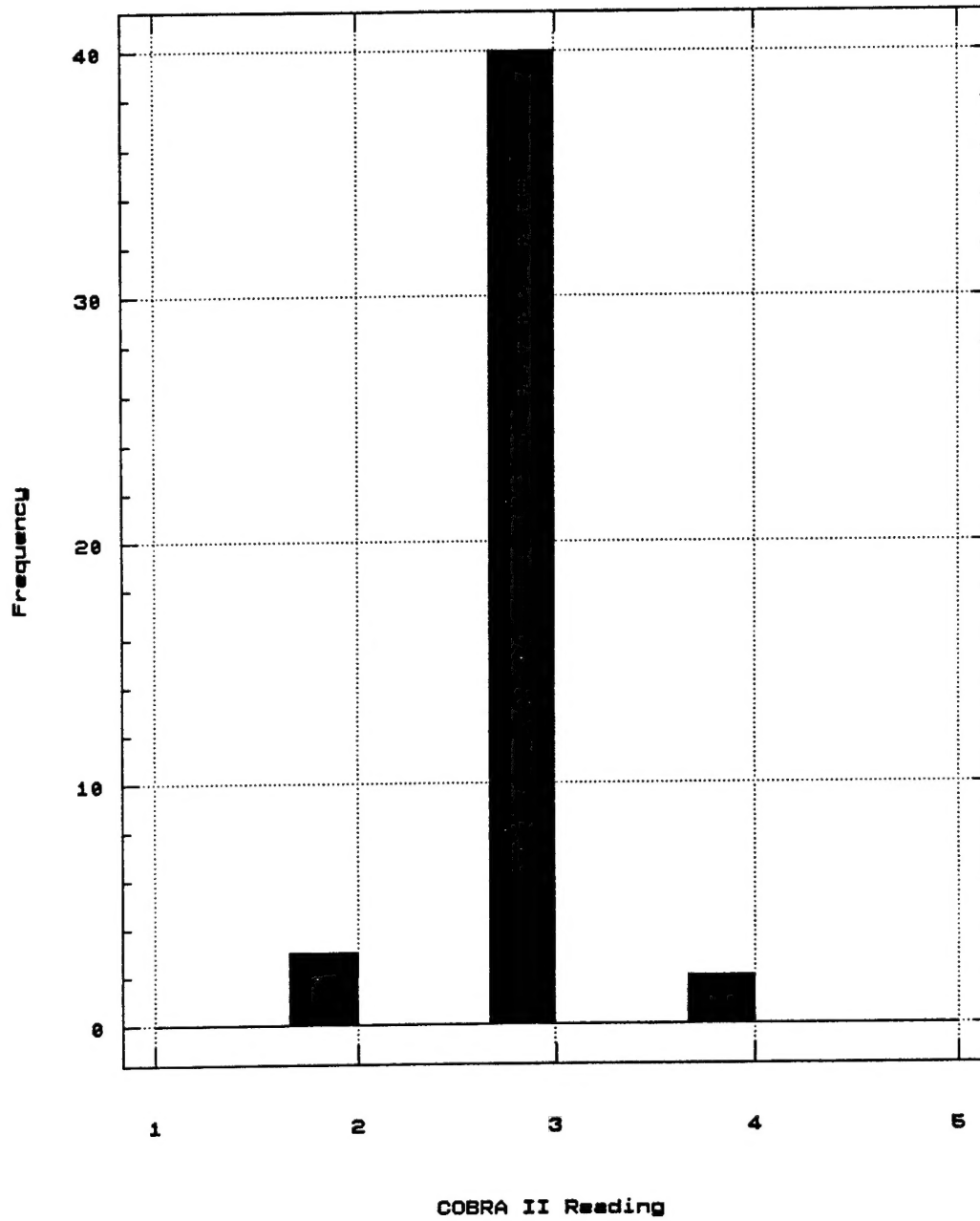
10/01/97

09:09:32 AM

Row	Location	Sample1	Sample2	Sample3
1	Seymour Johnson	3.	7.	13.
2	Seymour Johnson	3.	7.	13.
3	Seymour Johnson	3.	7.	13.
4	Seymour Johnson	3.	7.	13.
5	Seymour Johnson	3.	7.	13.
6	Elmendorf	3.	10.	15.
7	Elmendorf	4.	8.	16.
8	Elmendorf	4.	9.	15.
9	Elmendorf	3.	9.	16.
10	Elmendorf	3.	9.	16.
11	Nellis1	3.	9.	16.
12	Nellis1	3.	9.	16.
13	Nellis1	3.	9.	17.
14	Nellis1	3.	9.	16.
15	Nellis1	3.	9.	17.
16	Nellis2	3.	8.	15.
17	Nellis2	3.	8.	15.
18	Nellis2	3.	8.	15.
19	Nellis2	3.	9.	15.
20	Nellis2	2.	8.	15.
21	Wright-Patterson	3.	9.	15.
22	Wright-Patterson	3.	9.	15.
23	Wright-Patterson	3.	9.	15.
24	Wright-Patterson	3.	9.	15.
25	Wright-Patterson	3.	9.	15.
26	Eglin	2.	9.	15.
27	Eglin	2.	9.	15.
28	Eglin	3.	8.	16.
29	Eglin	3.	8.	16.
30	Eglin	3.	9.	16.
31	Langley1	3.	8.	14.
32	Langley1	3.	8.	13.
33	Langley1	3.	8.	14.
34	Langley1	3.	8.	14.
35	Langley1	3.	8.	14.
36	Langley2	3.	8.	16.
37	Langley2	3.	8.	15.
38	Langley2	3.	8.	15.
39	Langley2	3.	8.	14.
40	Langley2	3.	8.	15.
41	Luke	3.	9.	17.
42	Luke	3.	9.	17.
43	Luke	3.	9.	18.
44	Luke	3.	10.	17.
45	Luke	3.	10.	17.

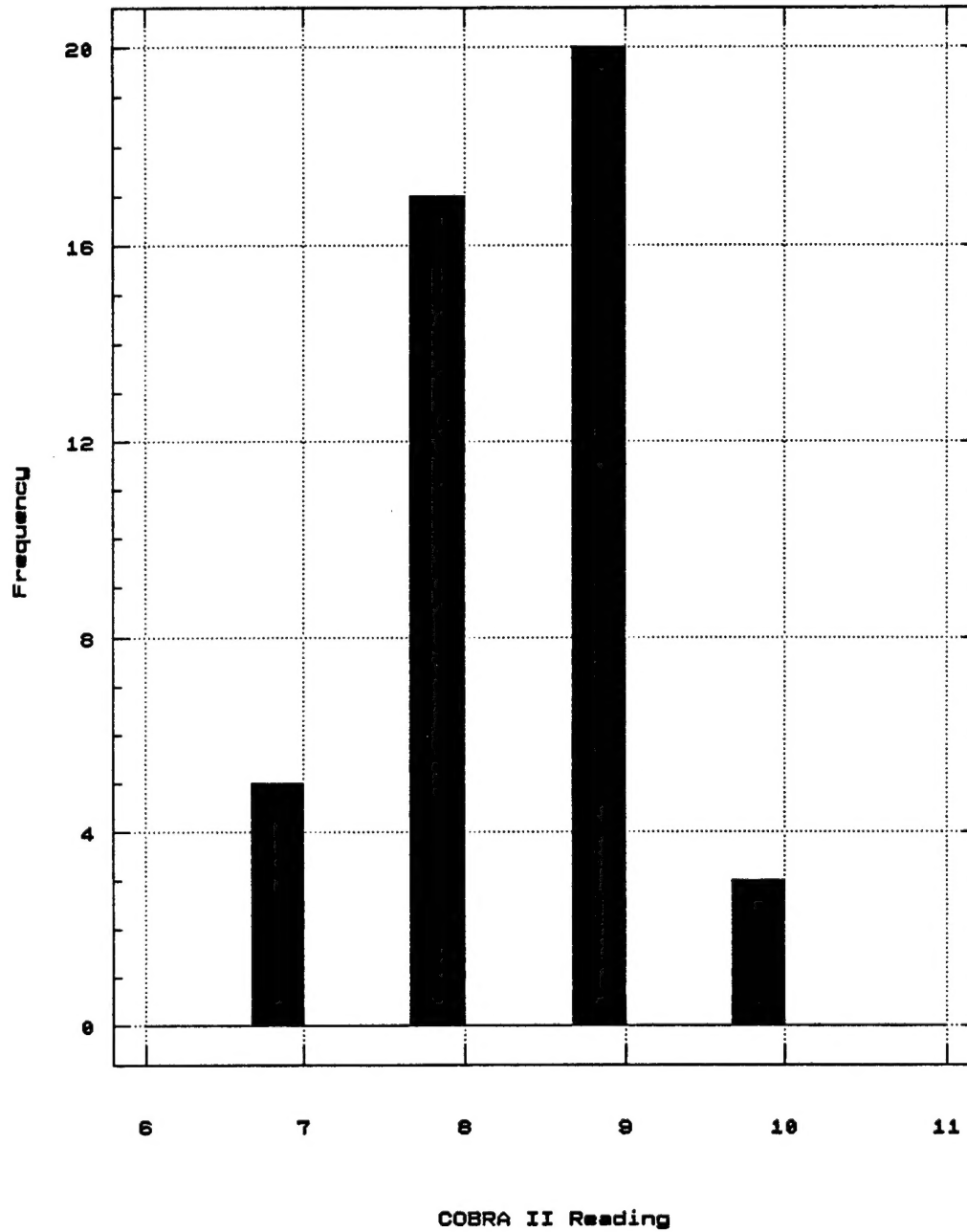
Frequency Histogram

Sample 1



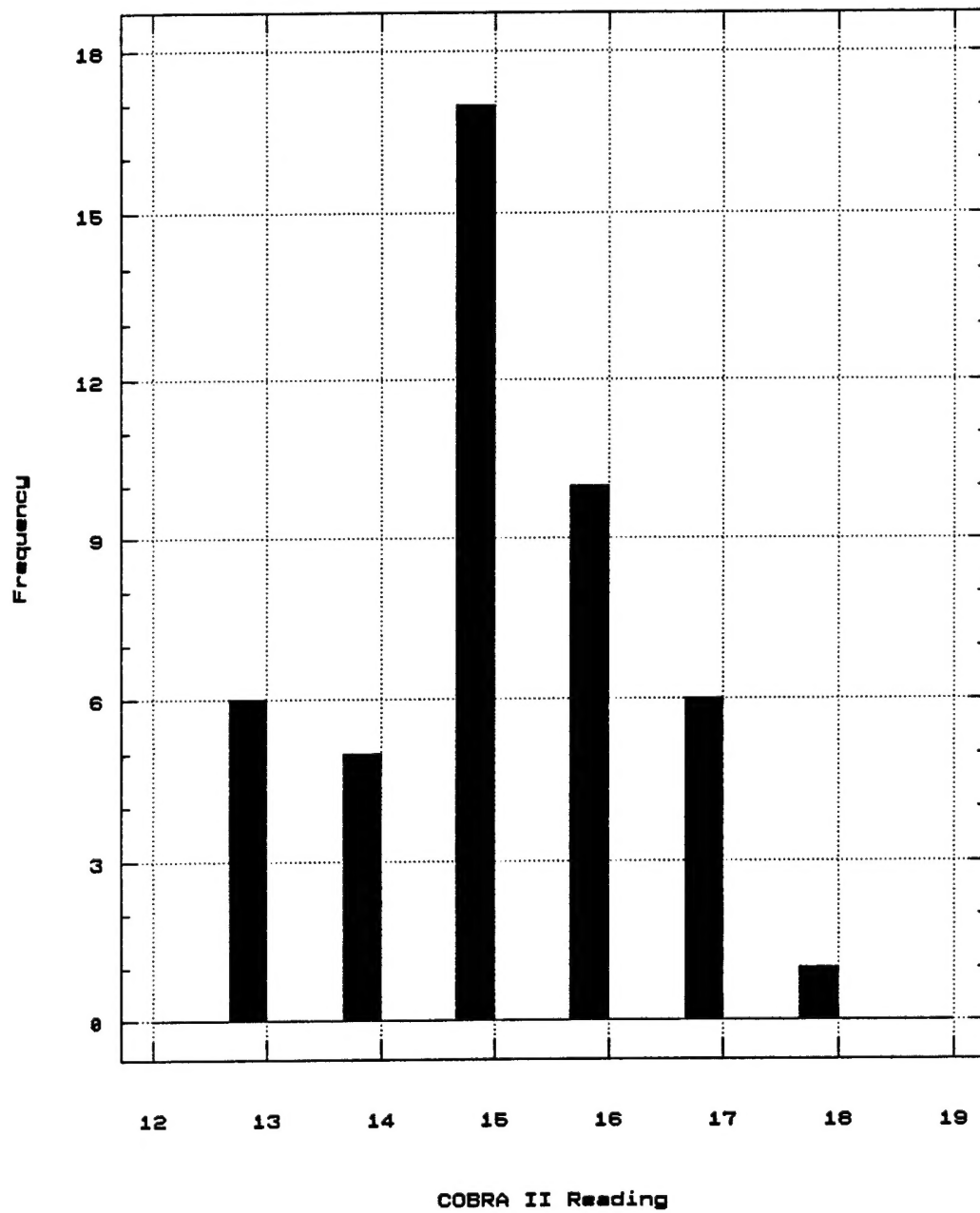
Frequency Histogram

Sample 2



Frequency Histogram

Sample 3



Three-D Histogram
COBRA II RMS Lab Values

